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1. Your reference PH/P18518GB

2. Patent application number
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27 JAN 2003

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*
 SWITCHED RELUCTANCE DRIVES LIMITED
East Park House, Otley Road, Harrogate, HG3 1PR,
England.
Patents ADP number *(if you know it)* 04010713001

If the applicant is a corporate body, give the country/state of its incorporation

GREAT BRITAIN

4. Title of the invention

A VARIABLE RELUCTANCE GENERATOR5. Name of your agent *(if you have one)*
 Kilburn & Strode
20 Red Lion Street
London
WC1R 4PJ

"Address for service" in the United Kingdom to which all correspondence should be sent
(including the postcode)

Patents ADP number *(if you know it)*

125001

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Country

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Description 13

Claim(s) 3

Abstract 1

Drawing(s) 12 + 12 *H*

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11.

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Signature *Peter Hale*

Date 27.1.2003.

12. Name and daytime telephone number of person to contact in the United Kingdom

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A Variable Reluctance Generator

The present invention generally relates to a reluctance machine operated as a generator. More particularly, the present invention relates to the operation of a
5 variable reluctance generator which is able to generate into a load without the use of active switches in its phase winding circuits.

The characteristics and operation of switched reluctance systems are well known in the art and are described in, for example, "The characteristics, design
10 and application of switched reluctance motors and drives" by Stephenson and Blake, PCIM'93, Nürnberg, 21-24 June 1993, incorporated herein by reference. Figure 1(a) shows a typical switched reluctance drive in schematic form, where the switched reluctance machine 12 is connected to a load 19. The DC power supply 11 can be rectified and filtered AC mains or a battery or some other
15 form of electrical storage. The DC voltage provided by the power supply 11 is switched across the phase windings 16 of the machine 12 by a power converter 13 under the control of the electronic control unit 14. The switching must be correctly synchronised to the angle of rotation of the rotor for proper operation of the drive, and a rotor position detector 15 is typically employed to supply
20 signals corresponding to the angular position of the rotor. The rotor position detector 15 may take many forms, including that of a software algorithm, and its output may also be used to generate a speed feedback signal. The presence of the position detector and the use of an excitation strategy which is completely dependent on the instantaneous position of the rotor leads to these
25 machines having the generic description of "rotor position switched".

Many different power converter topologies are known, several of which are discussed in the Stephenson paper cited above. One of the most common configurations is shown for a single phase of a polyphase system in Figure 2, in
30 which the phase winding 16 of the machine is connected in series with two

active switching devices 21 and 22 across the busbars 26 and 27. Busbars 26 and 27 are collectively described as the “DC link” of the converter. Energy recovery diodes 23 and 24 are connected to the winding to allow the winding current to flow back to the DC link when the switches 21 and 22 are opened.

- 5 A low-value resistor 28 is connected in series with the lower switch to act as a simple current transducer. A capacitor 25, known as the “DC link capacitor”, is connected across the DC link to source or sink any alternating component of the DC link current (ie the so-called “ripple current”) which cannot be drawn from or returned to the supply. In practical terms, the capacitor 25 may
10 comprise several capacitors connected in series and/or parallel and, where parallel connection is used, some of the elements may be distributed throughout the converter.

Figure 3 shows typical waveforms for two operating cycles of the circuit shown

- 15 in Figure 2 when the machine is in the motoring mode. Figure 3(a) shows the voltage being applied at the “on angle” θ_{on} for the duration of the conduction angle θ_c when the active switches 21 and 22 are closed. Figure 3(b) shows the current in the phase winding 16 rising to a peak and then falling slightly. At the end of the conduction period, the “off angle” θ_{off} is reached, the switches
20 are opened and the current transfers to the diodes, placing the inverted link voltage across the winding and hence forcing down the flux and the current to zero. At zero current, the diodes cease to conduct and the circuit is inactive until the start of a subsequent conduction period. The current on the DC link reverses when the switches are opened, as shown in Figure 3(c), and the
25 returned current represents energy being returned to the supply. The shape of the current waveform varies depending on the operating point of the machine and on the switching strategy adopted. As is well-known and described in, for example, the Stephenson paper cited above, low-speed operation generally involves the use of current chopping to contain the peak currents, and
30 switching off the switches non-simultaneously gives an operating mode

generally known as "freewheeling".

As is well known in the art, switched reluctance machines can be operated in the generating mode. A typical arrangement is shown in Figure 1(b), where
5 the load 19 of Figure 1(a) becomes the prime mover 19', such as an internal combustion engine, supplying mechanical energy. The power supply 11 becomes an electrical load 11', accepting energy from the electrical machine 12 through the power converter 13. In general, the phase currents are mirror images (in time) of the phase currents in the motoring mode. Such systems are
10 discussed in, for example, "Generating with the switched reluctance motor", Radun, Proceedings of the IEEE 9th Applied Power Electronics Conference, Orlando, Florida, 13-17 Feb 1994, pp 41 – 47. Figure 4(a) illustrates a flux waveform and the corresponding current waveform when the system is motoring and Figure 4(b) illustrates the corresponding waveforms for
15 generating. It will be seen from Figure 4(b) that the machine requires a "priming" or magnetising flux to be established (along with the necessary current to support this flux) before the energy is returned to the DC link. In other words, some electrical energy is required from the DC link to prime the machine before it is able to convert a larger amount of mechanical energy back
20 to the DC link.

Though there are many topologies used for power converters for switched reluctance machines, all of them use a certain number of active switches, and these switches represent a significant portion of the cost of the converter.
25 Considerable effort over many years has been put into reducing the number of switches per phase.

The present invention is defined in the accompanying independent claims. Some preferred features of the invention are recited in the claims respectively
30 dependent thereon.

According to one embodiment of the invention useful electrical power is generated by a variable reluctance machine without actuating conventional power switches. A bias flux is introduced into the magnetic circuit, the magnitude of which flux varies with rotor position. Generation can be
5 achieved by limiting the phase voltage to a magnitude below that otherwise induced in the phase by the bias flux. Thus, a method and apparatus for generating electrical power can be achieved either without active switches being present in the power converter of the machine, or with power switches present but that are not being actuated, and therefore effectively not present,
10 while this mode is in operation.

The difference in flux linkage between the bias flux and that associated with the limited voltage represents a flux that has to be supported by a current, which is caused to flow in the phase winding. Hence the present invention
15 generates electrical power in the or each phase of the machine. The phase voltage can be limited by a semiconductor device, such as a diode or diode bridge arrangement connected with the phase. In such a system the semiconductor device also serves to restrict the flow of current in the phase to one direction, thereby producing a usable rectified source of electrical power.
20 Another device for limiting the phase voltage is a thyristor which is, of course, controllable as to the level at which it commutes.

The flux in the magnetic circuit can be biased by means of one or more coils magnetically coupled to some or all of the phase windings of the machine. The
25 excitation of the coil can be constant or variable. Another way of biasing the flux is to arrange a permanent magnet, or magnetisable element, in relation to the phase(s).

The invention has clear advantages in that it avoids the need to actuate power
30 switches in the way a conventional switched reluctance generator would require it. The conventional power switches in a switched reluctance generator

need not be present according to the present invention. Alternatively, the mode of operation in accordance with the present invention can be set up in a conventional switched reluctance drive system and used temporarily as one of a range of operating modes. For example, the drive for an electric vehicle or
5 hybrid electric vehicle may include a switched reluctance drive as the, or part of the, prime mover. In such systems, the switched reluctance drive has been used both as a source of motive power and as a generator at appropriate times. The present invention allows the same drive to be used with the power switches simply rendered inactive, rather than not being present.

10

In accordance with a particular form of the present invention there is provided a method of operating a variable reluctance machine as a generator, the machine having at least one phase winding, the method comprising: creating a bias flux linking the or at least one phase winding; and limiting the phase
15 voltage to a magnitude below that otherwise induced in the phase winding by the bias flux.

The invention also extends to a variable reluctance machine having a first part with at least one phase winding and a second part which is arranged to move
20 relative to the first part to generate electrical power; means for creating a bias flux linking the or at least one phase winding; and means for limiting the magnitude of the phase voltage below that otherwise induced in the phase winding by the bias flux.

25 The phase voltage may be limited initially to zero volts. This may be done conveniently with the use of diodes to limit the phase voltage as referred to above. Furthermore, the diodes also serve to restrict the flow of current in the phase to one direction, thereby providing rectified output electrical power. Such a diode may be part of a rectifier circuit providing, for example, full-wave
30 rectification.

The output of the variable reluctance generator according to the present invention can be controlled either by controlling the generator speed, the bias flux created in the at least one phase, or the voltage across the DC link.

- 5 Other aspects and advantages of the invention will become apparent upon reading the following detailed description of exemplary embodiments of the invention and upon reference to the accompanying drawings, in which:

Figure 1(a) is a schematic drawing of a prior art switched reluctance drive operating as a motor;

- 10 Figure 1(b) is a schematic drawing of a prior art switched reluctance drive operating as a generator;

Figure 2 is a prior art excitation circuit for the switched reluctance machine of Figure 1(a) or (b);

Figure 3(a) is a phase voltage waveform for the circuit shown in Figure 2;

- 15 Figure 3(b) is the phase current waveform corresponding to Figure 3(a);

Figure 3(c) is the supply current waveform corresponding to Figure 3(a);

Figure 4(a) and Figure 4(b) show flux and current waveforms for motoring and generating respectively;

- 20 Figure 5 shows generating system according to one embodiment of the invention;

Figure 6(a) shows a schematic view of the laminations and windings of a switched reluctance machine;

Figure 6(b) shows a schematic view of the laminations and windings of another switched reluctance machine;

- 25 Figure 7 shows the basic inductance, flux-linkage and voltage waveforms corresponding to one embodiment of the invention;

Figure 8 shows flux-linkage, voltage and current waveforms corresponding to the embodiment of the invention;

Figure 9(a) shows a modification of the circuit of Figure 5;

- 30 Figure 9(b) shows a further modification of the circuit of Figure 5;

Figure 10 shows a yet further modification of the circuit of Figure 5;

Figure 11 shows a set of waveforms corresponding to the operation of Figure 10;

Figure 12 shows a circuit combining elements of Figures 9(a) and 10;

Figures 13-15 show sets of waveforms corresponding to the operation of Figure 5 12 according to different operating conditions; and

Figures 16(a) and (b) show delta and star connections of a variable reluctance generator according to one aspect of the invention.

10 Figure 5 is a schematic diagram of one phase of a variable reluctance machine system according to one embodiment of the invention. The system may have only one phase or it may be polyphase. The components which are the same as in the prior art system of Figure 2 are given the same numerals. In addition, the machine has a bias winding 18 fed by a constant current source 20. The magnetic polarity of the bias winding 18 with respect to the phase 15 winding 16 is denoted by dots in the conventional way. The current in the bias winding is I_b , and the voltage, V_b , induced in it by the phase voltage, V_{ph} , by virtue of its magnetic coupling, is given by

$$V_b = V_{ph} \cdot N_b / N_{ph} \quad (1)$$

Where N_b is the number of turns in the bias winding 18 and

20 N_{ph} is the number of turns in the phase winding 16.

In physical terms, the bias winding may comprise a single winding spanning half an electrical pitch of the machine, as shown schematically in Figure 6(a) for the example of a machine having six stator poles 61 and four rotor poles 64.

25 A rotor 66 is mounted on a shaft 68 to rotate within the stator. The stator poles carry coils 63, which are conventionally connected in series or parallel to provide three phase windings, one of which is represented as 16 in Figure 5. The bias winding 18 comprises a single coil 65 placed across the diameter of the machine, therefore embracing half the poles in a diametrically arranged loop.

Alternatively, as shown in Figure 6(b), the bias winding may comprise multiple coils 65' on all, or at least some, of the poles, each embracing the pole in the same way as, but distinct from the coils 63 of the phase winding 16 on the same pole. The coils 65' are connected in series so that the current in each 5 one is the same. In this case, the series connection of the six bias coils is the equivalent of the single coil 65 in Figure 6(a).

It will be seen by inspection of the flux paths that these two arrangements are magnetically similar, and the choice between them would result from a 10 consideration of such factors as size of the end-windings and the available space in the machine.

Other forms of bias winding may be used. For example, the winding may comprise gramme-ring type windings around the back-iron of the stator in 15 which magneto motive force supporting the bias flux is applied around the back iron. In all cases, however, the bias winding sets up a flux from one half of the electrical pitch of the machine towards the other. For all these different bias winding arrangements the flux pattern at the air gap is the same. In a polyphase machine, the total flux will be essentially constant in magnitude for 20 a constant bias current. As an alternative source of bias flux, a permanent magnet could be used in place of the bias winding 18, but such an arrangement would lack the flexibility of a wound coil in which the current can be controlled.

25 The operation of the machine will now be explained using the circuit of Figure 5. To simplify the description, it will be assumed that the machine is magnetically linear. It is also assumed that the current source 20 is ideal in that it can hold the bias current I_b constant regardless of any voltage induced in the bias winding 18. The switches 21 and 22 are open.

The inductance profile of phase winding 16 is shown in Figure 7. The profile is defined by the magnetic geometry of the laminations of the machine. Since inductance is defined as flux-linkage per amp of excitation, the flux in the phase winding is given by

5

$$\Psi_{ph} = L I_b \quad (2)$$

and is shown in Figure 7 for an arbitrary value of I_b . It follows that, for constant current I_b the flux-linkage curve has the same form as the inductance. From Faraday's Law, the voltage induced in the phase winding can be deduced as

10

$$V_{ph} = d\Psi_{ph} / dt = \omega d\Psi_{ph} / d\theta \quad (3)$$

where θ is the angular displacement of the rotor and ω is the speed, $d\theta/dt$. Since the slope of the inductance profile is piecewise linear, the induced voltage has the rectangular form shown in Figure 7. The magnitude of the voltage, from Equations 2 and 3, is proportional to the speed and the bias current. As the voltage is increased, there comes a point where it equals the (constant) magnitude of the DC link voltage. By inspection of Figure 5, the diodes 23,24 will become forward biased when the negative voltage excursion equals the DC link voltage, thus clamping the phase voltage. This is shown in Figure 8. By Equation 3, the clamping of V_{ph} clamps $d\Psi_{ph} / dt$ to a shallower slope, as shown by line Y, than it would otherwise have had, as shown by line X. The difference in flux-linkage between the two lines represents a flux which has to be supported by a current flowing in the diodes, as shown. Note that the voltage waveforms and current waveforms are asymmetrical.

25

Since the switches 21 and 22 are not used, the circuit can be simplified to that shown in Figure 9(a) or 9(b) if the machine is not used in the motoring mode. This yields a power converter for a variable reluctance generator which has no active switches connecting it to the DC link. The DC link capacitor 25 may be replaced by a resistor 90 which simply dissipates the generated energy, allowing the system to be used as a brushless brake. In this case, the diodes

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clamp the negative excursion of the voltage to $-IR$, which is initially zero. Alternatively, the capacitor 25 can be replaced by a storage battery.

- In another embodiment of the invention, shown in Figure 10, the diodes 23 and 24 are reconnected to replace the switches 21 and 22. As before, one or other of the diodes can be deleted. This embodiment clamps the positive-going voltage excursion to the DC link voltage, so the gradient of the increasing flux is modified, as shown in Figure 11. In this case, the flux linkage is reduced from what it would otherwise be, so the current flowing is in the opposite direction in the phase winding. Because the new flux linkage line falls underneath the dead zone of the inductance profile, the shape of the current is different from that described earlier. It will be noted that although the slope of the flux-linkage changes sign, the current is continuous and unidirectional.
- It is possible to combine the currents of Figure 8 and Figure 11 by using four diodes connected as in Figure 12. These are effectively connected in the form of a single-phase bridge, so it would be possible to use a standard component package for this duty.
- Figure 13 shows the current waveforms of Figures 8 and 11 combined to give the current flowing in the DC link. It will be noted that the action of combining the currents delays the start of current from Figure 8, and that the composite waveform is discontinuous in part of the minimum inductance region. As the bias current or the speed is increased or the DC link voltage is decreased, there comes a point, shown in Figure 14, beyond which current is always supplied from one or other pair of diodes.

A further increase in excitation or speed or further reduction of the DC link voltage brings the machine into a new operating mode, which it enters through a transient state. In this respect, it is akin to the continuous current mode of conventional switched reluctance drive systems as disclosed in EP 0537761A

which is incorporated herein by reference. When a steady state has been reached, as shown in Figure 15, the length of time the flux takes to increase is exactly matched by the length of time taken to decrease and the locus of the point of change from increasing to decreasing follows the original flux linkage 5 decrease. Since the slopes of increase and decrease are identical, the operating point is defined for any excitation level. Note that the two diode currents are still, in general, unequal, since the inductance profile is not symmetrical about a horizontal axis. This mode is inherently stable, since any perturbation will drive the increasing flux-linkage line to a smaller value and 10 the decreasing flux-linkage line to a larger value, thus stabilising the system.

It will be noted that the system described above has no need of shaft position information, since the diodes self-commutate when the currents fall to zero. This represents a further cost saving. It will be noted that in the embodiments 15 shown there is no connection between the bias winding and the phase windings of the machine, i.e. there is galvanic isolation between them. This may be a significant safety benefit.

It will be appreciated that, while a single phase of a system has been used for 20 illustration above, this is purely exemplary and the principles outlined above apply to any number of phases and any combination of numbers of stator and rotor poles. Where the system has three or more phases, alternative connections to the DC link are possible. For example, for a three-phase system, delta or star (wye) connections are possible, as shown in Figure 16(a) 25 and (b) respectively. Because the phase voltages are not symmetrical, the phase voltages in the delta connection only sum to zero under certain special conditions, so in general a circulating current will be present in the delta to compensate. Similarly, since the currents are not symmetrical, the phase currents in the star connection will only be equal under special conditions, so in 30 general the star point will move to accommodate this. With these connections, the diodes form a standard three-phase bridge, so, again, a

standard component module can be used.

Those skilled in the art will recognise that for phase numbers above three, corresponding ring and radial circuits are also possible.

5

In general, phase-controlled devices, such as thyristors or other silicon controlled rectifiers, could be used to replace some or all of the diodes to give a further degree of control. While such a system would still not require rotor position information (since the devices would turn off when the current crossed zero), it would introduce a complexity which runs counter to the simplicity of the invention.

10

In operation, it is assumed that the prime mover will spin the generator at some appropriate speed. To start the generator, the control system causes the appropriate level of current to flow in the bias winding. Current is then generated onto the DC link, the amount of power transferred being controlled by adjusting the speed of the machine and/or the magnitude of the bias current. Those skilled in the art will appreciate that conventional feedback methods can be used to control the output.

15

The descriptions above have been on the basis of a controlled unidirectional bias current I_b . This is likely to be the most useful embodiment of the invention, though it should be noted that it is possible to operate with alternating bias current. The profile of the phase flux-linkage will have a superimposed modulation which, depending on the length of the period of the alternating bias current compared with the period of the inductance cycle of the variable reluctance machine, will result in a corresponding modulation of the generated current. For the special case of the period of the bias current corresponding to the period of the phase flux linkage, there is an opportunity to reduce the number of diodes in the circuit, though this benefit is likely to be offset by the complexity of synchronising the two frequencies.

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While the circuits of Figures 9, 10, 12 & 16 have dispensed with the active switches used in the motoring mode, it will be clear that if they are retained the system can be operated as a generator both according to the invention and in a conventional switching mode without any re-configuration of the power converter.

The skilled person will appreciate that variation of the disclosed arrangements are possible without departing from the invention. Accordingly, the above description of several embodiments is made by way of example and not for the purposes of limitation. It will be clear to the skilled person that minor modifications can be made to the arrangements without significant changes to the operation described above. The present invention is intended to be limited only by the scope of the following claims.

CLAIMS:

1. A method of operating a variable reluctance machine as a generator, the machine having at least one phase winding, the method comprising:
 - 5 creating a bias flux linking the or at least one phase winding; and limiting the phase voltage to a magnitude below that otherwise induced in the phase winding by the bias flux.
2. A method as claimed in claim 1 further including restricting the flow of
 - 10 current in the phase winding to one direction.
3. A method as claimed in claim 2 in which the flow of current is restricted by at least one diode which also serves to limit the phase voltage.
 - 15 4. A method as claimed in claim 3 in which the diode is part of is a full-wave rectifier circuit.
 5. A method as claimed in any of claims 1 to 4 in which the phase current is caused to flow through a resistor.
 - 20 6. A method as claimed in any of claims 1 to 7 in which an electrical output of the machine is controlled by controlling the bias flux.
 7. A method as claimed in any of claims 1 to 5 in which the bias flux linking the or at least one phase is created with a bias coil or coils magnetically coupled to the phase winding.
 - 25 8. A method as claimed in claim 6 in which the machine is polyphase and the bias coil(s) is/are arranged to couple with a proportion of the phase windings of the machine.
 - 30

9. A method as claimed in claim 7 or 8 in which the bias flux is produced by a constant current in the or each bias coil.
10. A method as claimed in claim 8 in which the bias flux is produced by an
5 alternating current in the or each bias coil.
11. A method as claimed in any of claims 1 to 10 wherein the machine is connected to a power converter circuit.
- 10 12. A method as claimed in claim 11 in which the power converter circuit has no active switches.
13. A method as claimed in claim 11 in which the power converter circuit includes active switches which are kept open while the variable reluctance
15 machine is operated as a generator.
14. A method as claimed in any preceding claim including controlling the output power of the machine by controlling the speed of the machine.
- 20 15. A method as claimed in any preceding claim including controlling the output power of the machine by adjusting the magnitude to which the phase voltage is limited.
16. A variable reluctance machine having a first part with at least one phase
25 winding and a second part which is arranged to move relative to the first part to generate electrical power; means for creating a bias flux linking the or at least one phase winding; and means for limiting the magnitude of the phase voltage below that otherwise induced in the phase winding by the bias flux.
- 30 17. A machine as claimed in claim 16 including means for restricting the flow of current in the phase winding to one direction.

18. A machine as claimed in claim 17 in which the means for restricting and the means for limiting collectively comprise at least one diode.
- 5 19. A machine as claimed in claim 18 in which the at least one diode is serially connected with the at least one phase winding.
20. A machine as claimed in claim 19 in which the at least one diode is part of a full-wave rectifier circuit.
- 10 21. A machine as claimed in any of claims 16 to 20 in which the means for creating a bias flux comprise at least one bias coil magnetically coupled to the at least one phase winding.
- 15 22. A machine as claimed in claim 21 in which the machine is polyphase and the bias coil is arranged to couple with a proportion of the phases.
23. A machine as claimed in any of claims 21 or 22 including a constant current source connected to excite the or at least one bias coil.
- 20 24. A machine as claimed in any of claims 21 or 22 including an alternating current source connected to the bias coil.
25. A machine as claimed in any of claims 16 to 24 connected to a power converter circuit.
26. A generator as claimed in claim 25 in which the power converter has no active switches.
- 30 27. A generator as claimed in any of claims 16 to 26 including a resistive load connected across the or each phase winding.

ABSTRACT:

A variable reluctance generator has phase windings and a bias winding. By controlling the excitation produced by the bias winding, the speed of the
5 machine or the DC link, a power converter using only diodes can supply power to a DC bus.

10 Figure 10.



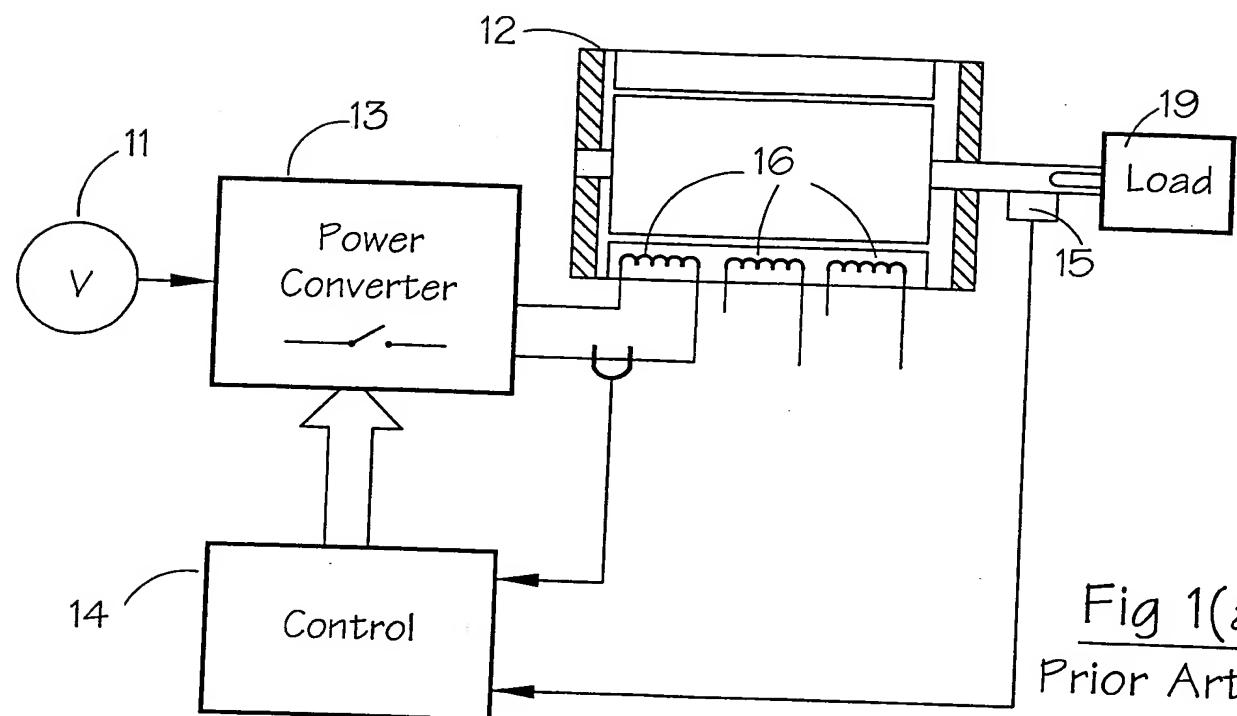


Fig 1(a)
Prior Art

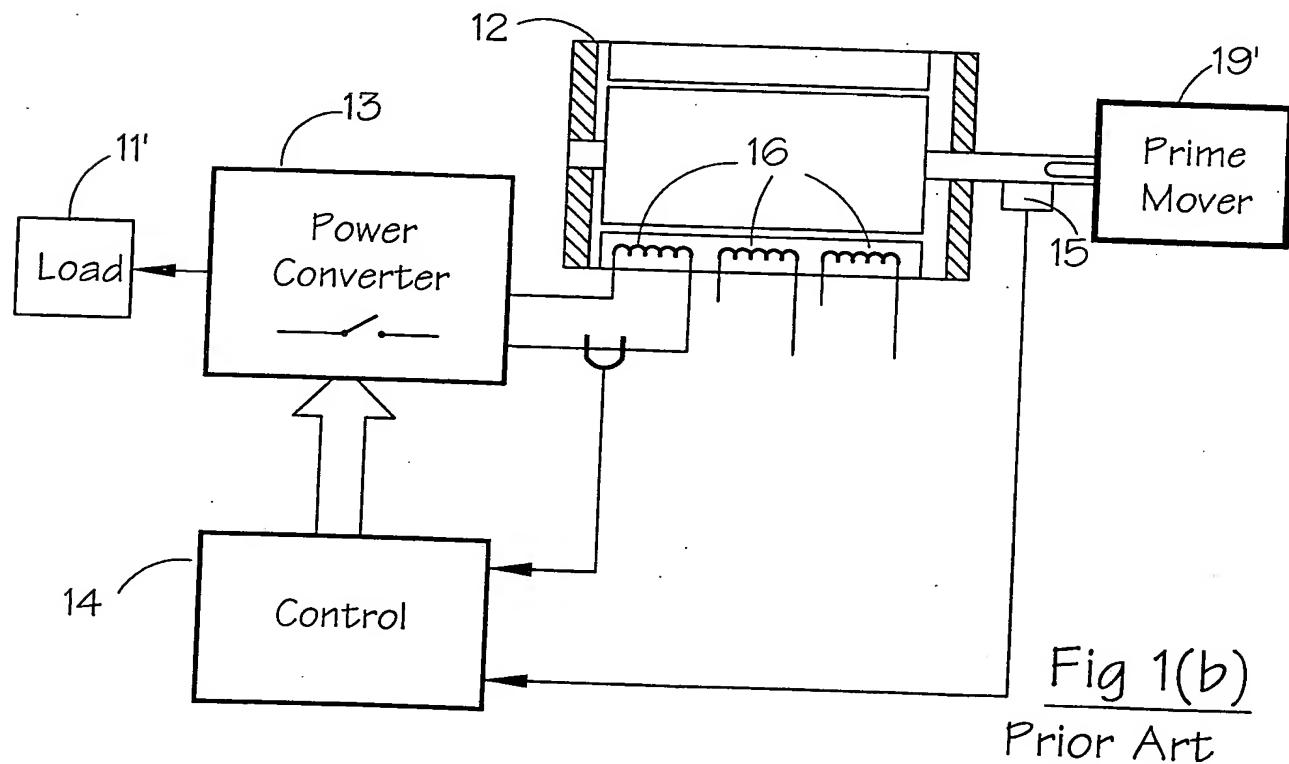


Fig 1(b)
Prior Art

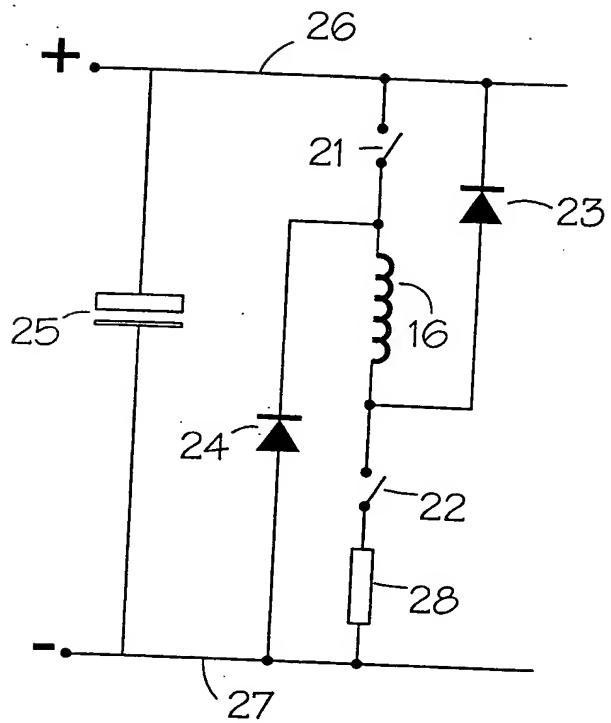


Fig 2
Prior Art

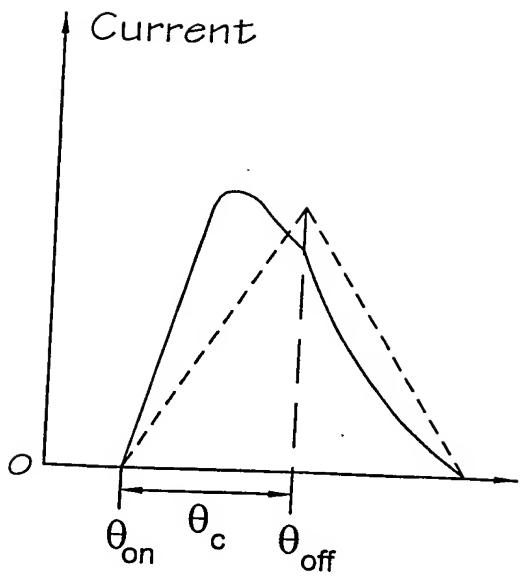


Fig 4a
Prior Art

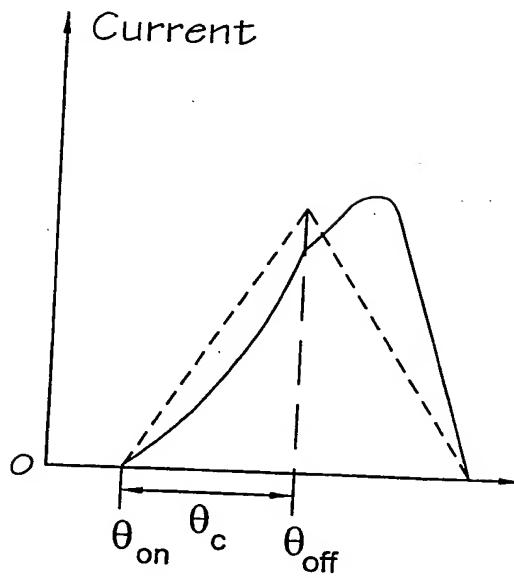


Fig 4b
Prior Art



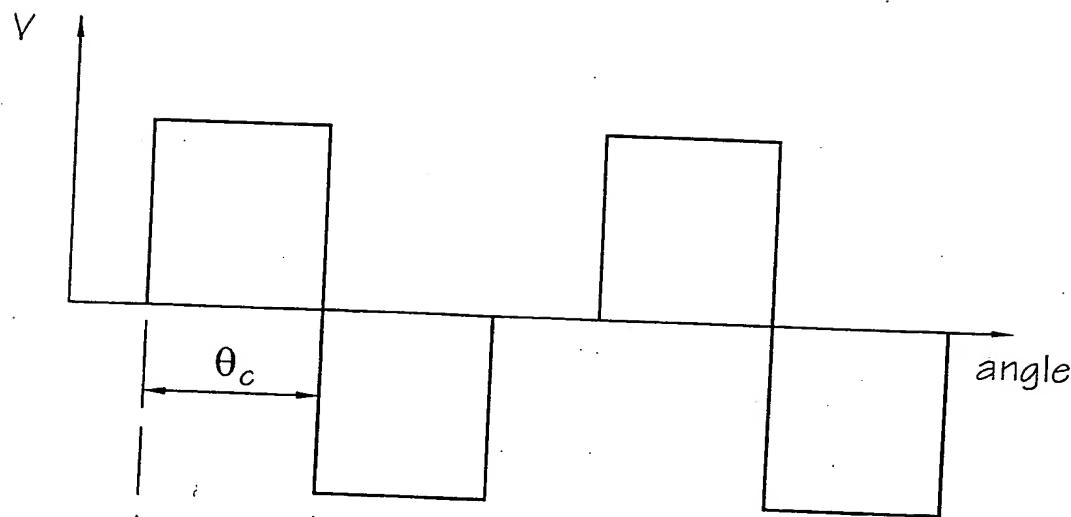


Fig 3(a)
Prior Art

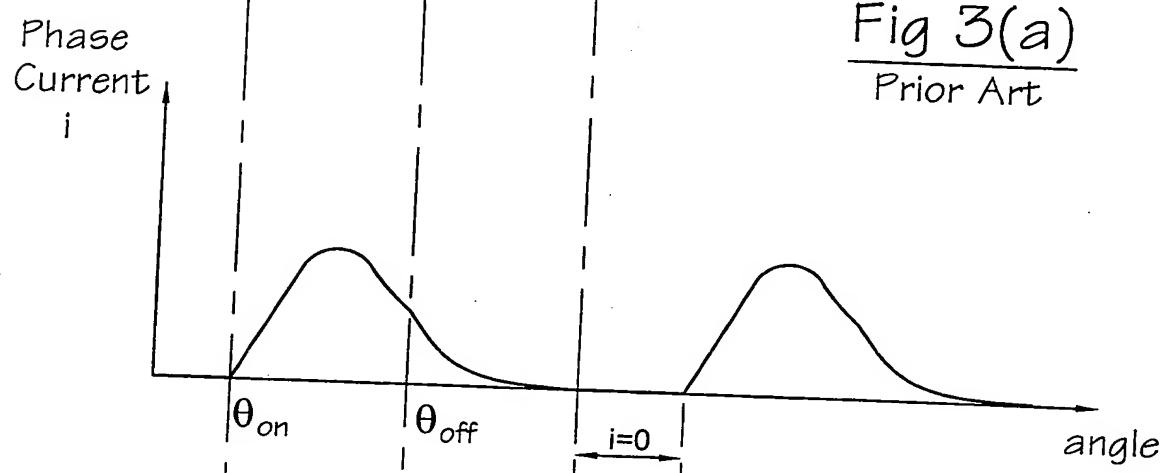


Fig 3(b)
Prior Art

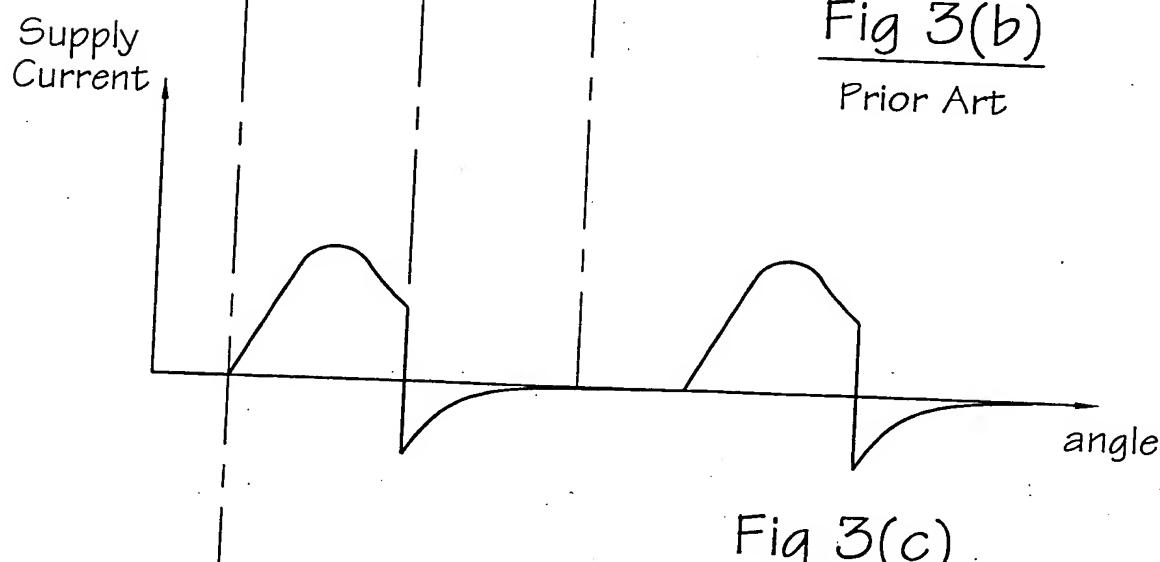
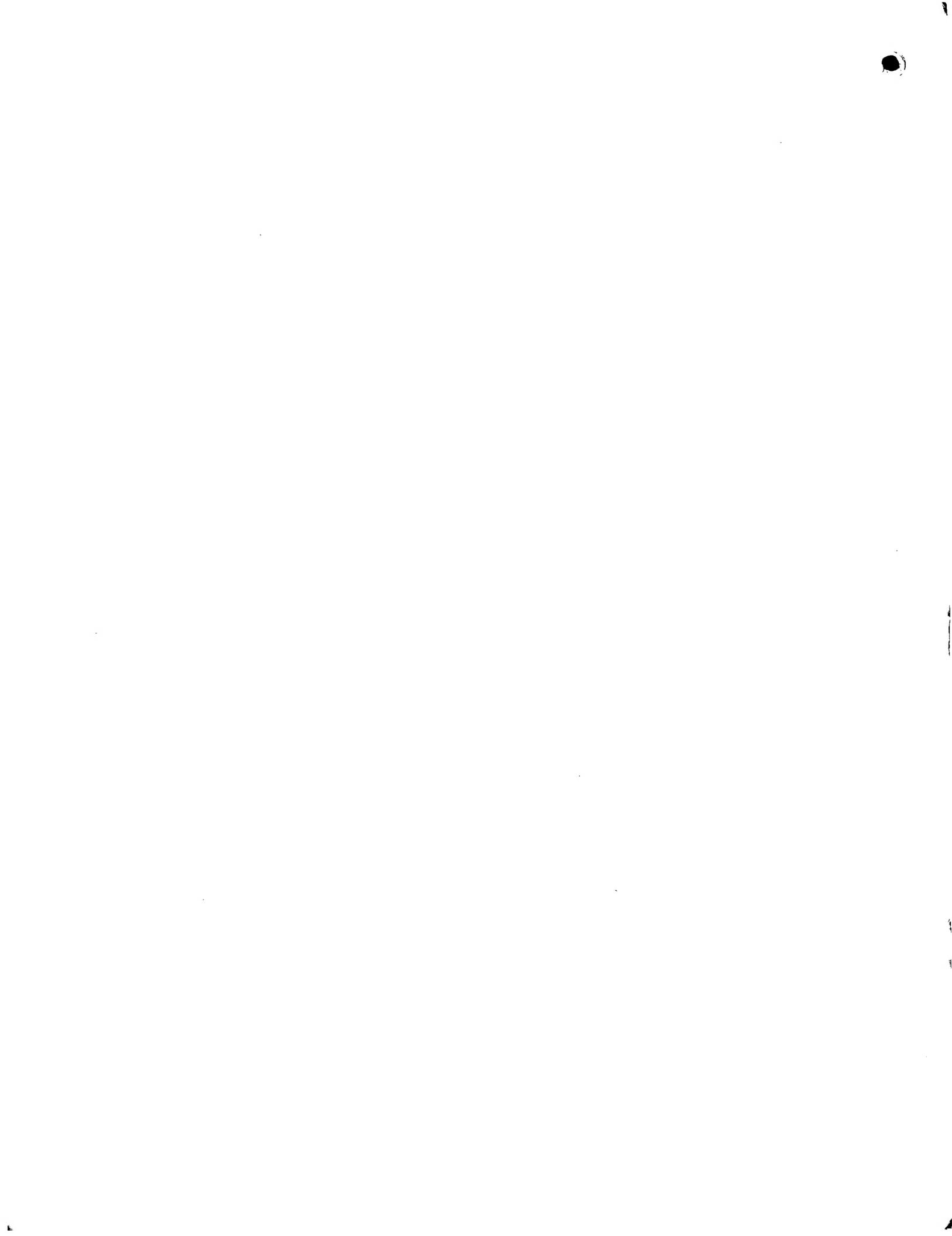


Fig 3(c)
Prior Art



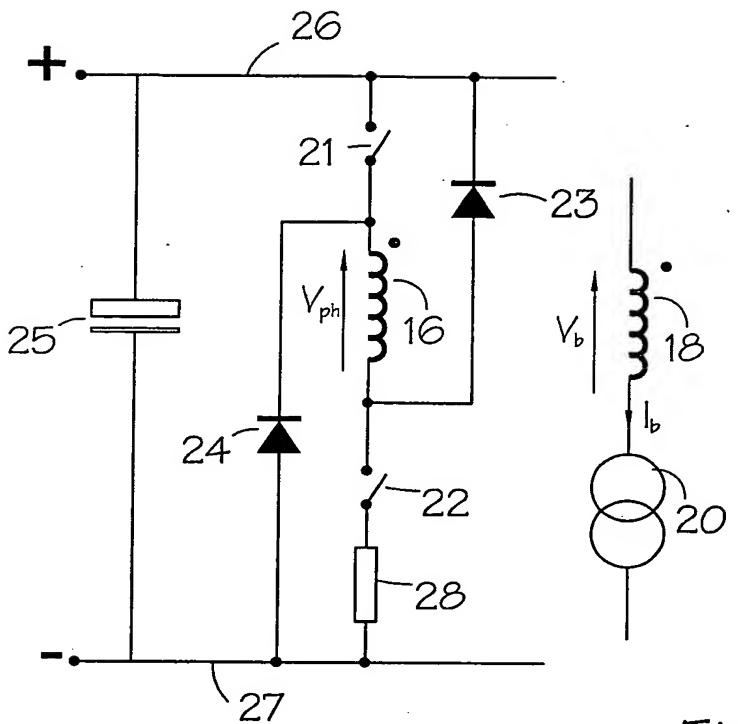


Fig 5

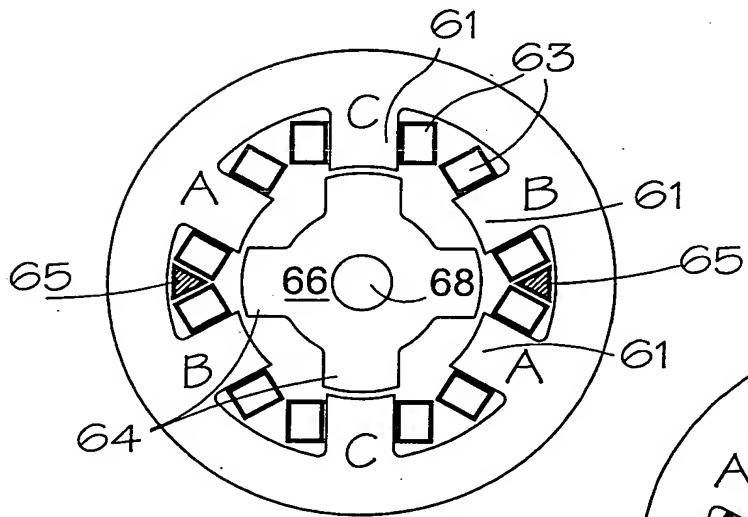


Fig 6(a)

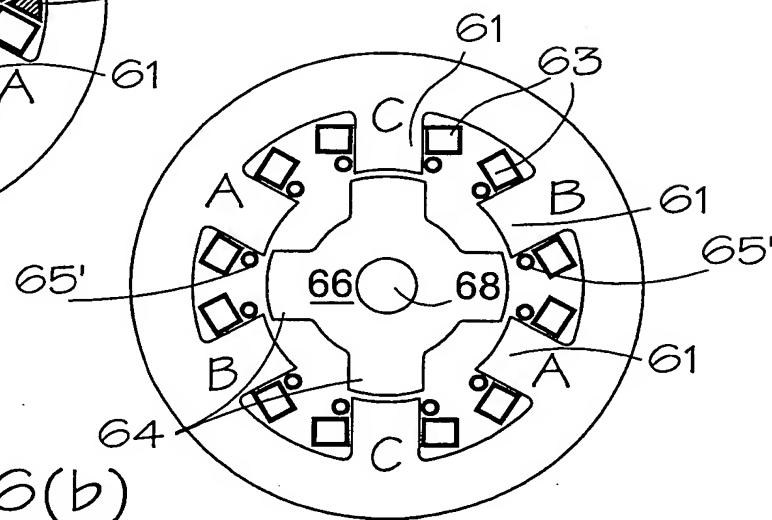


Fig 6(b)

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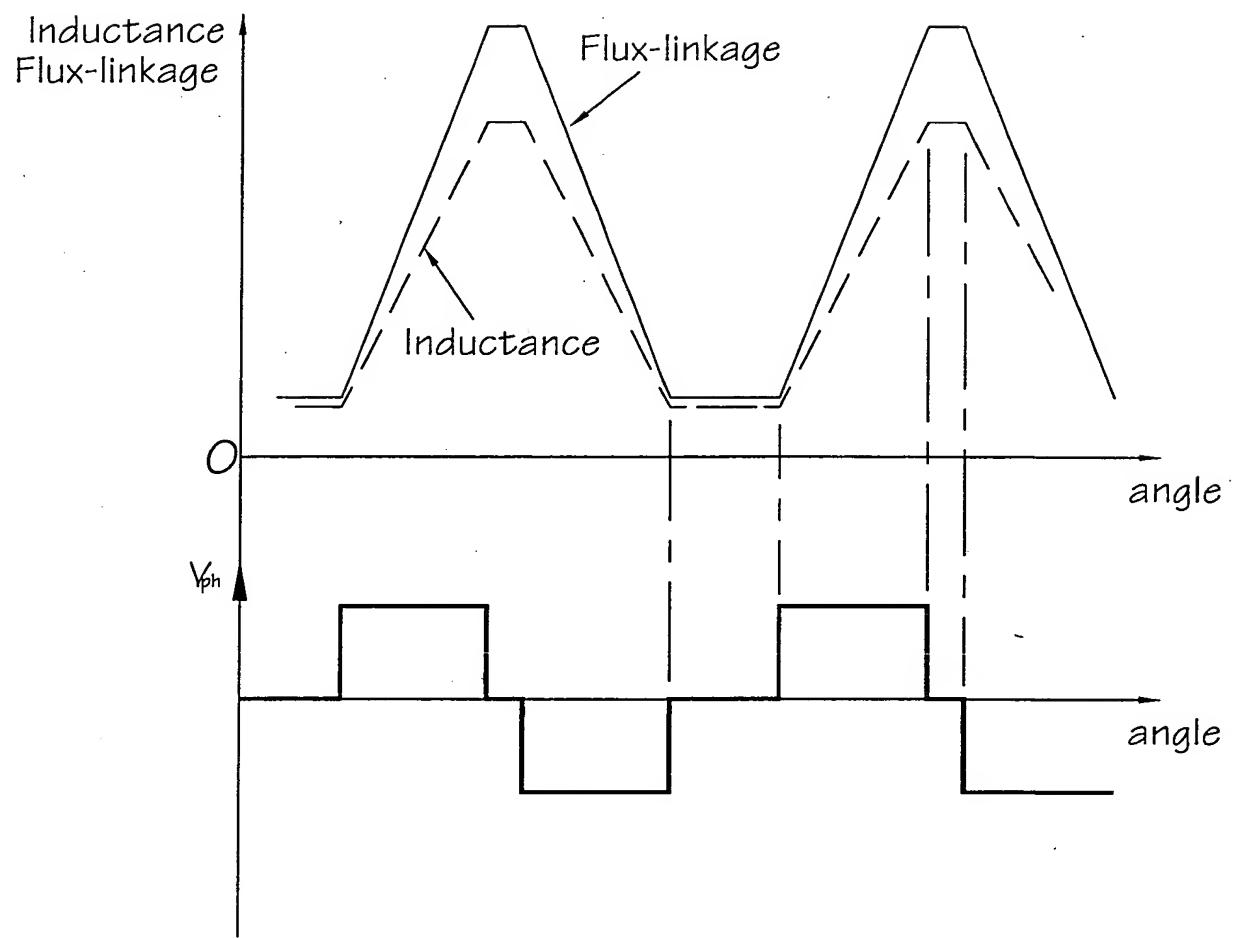


Fig 7



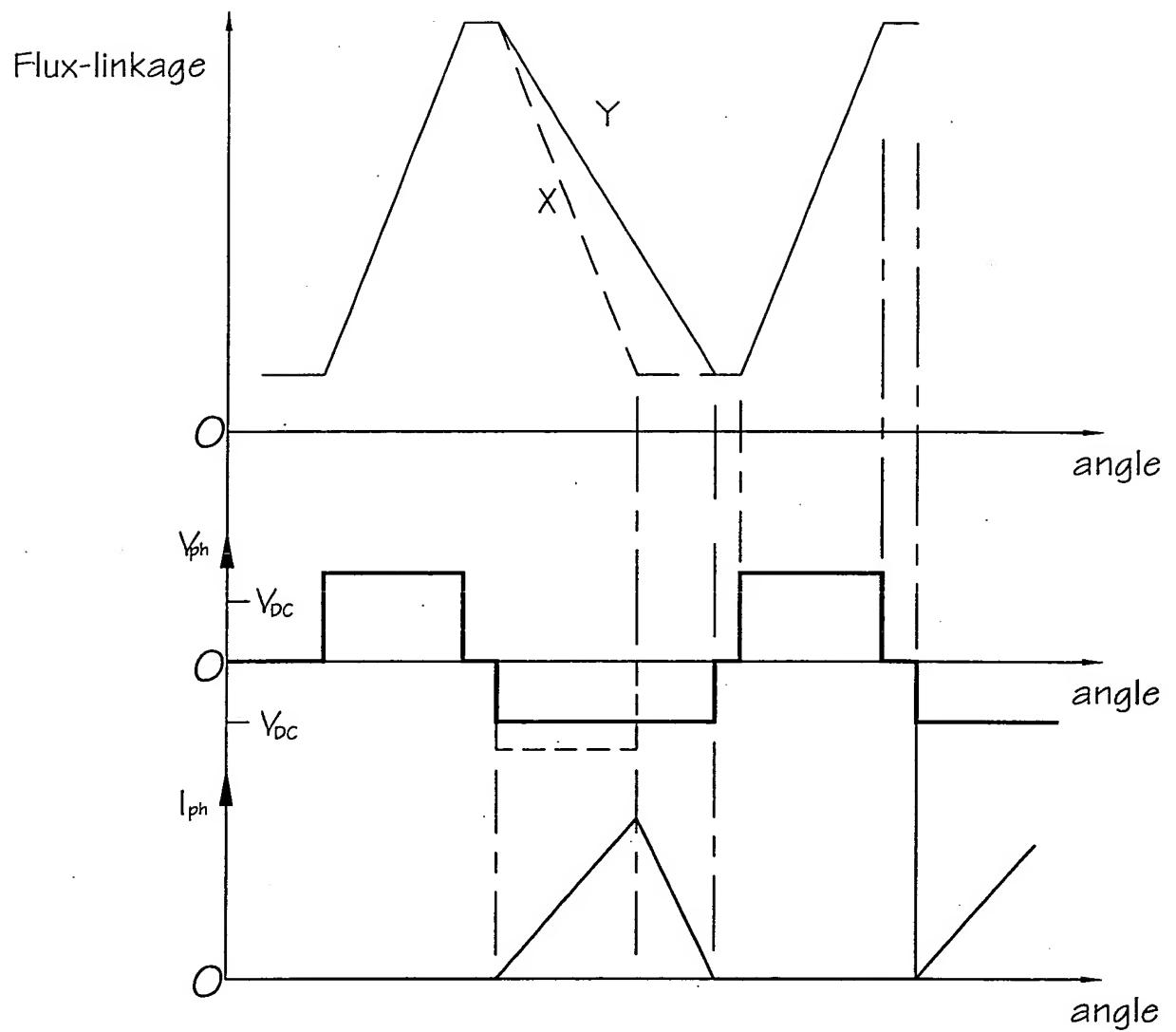


Fig 8



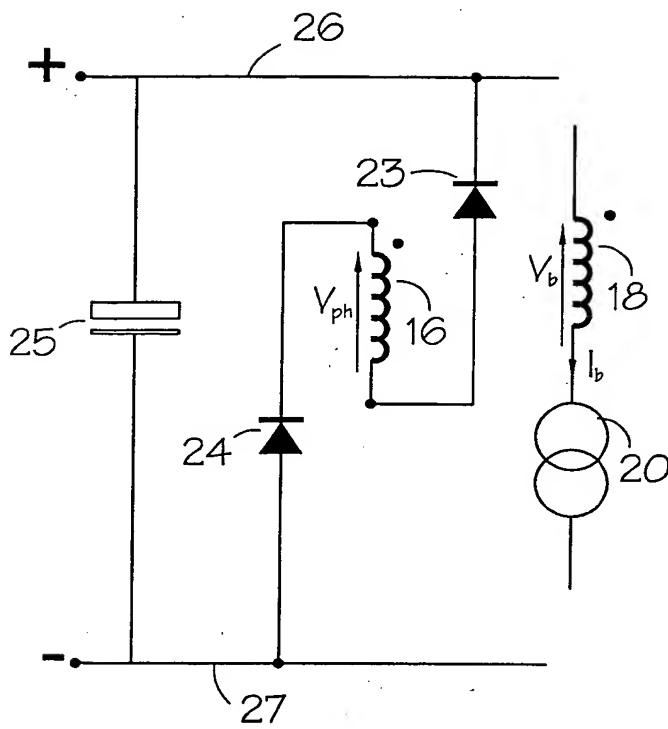


Fig 9(a)

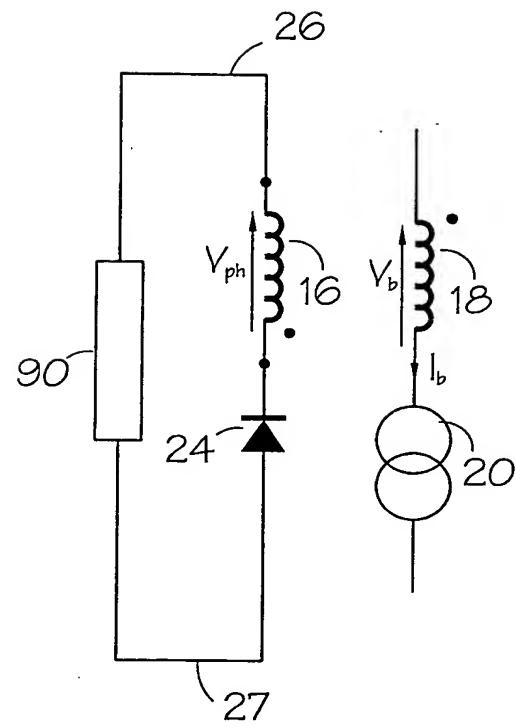


Fig 9(b)

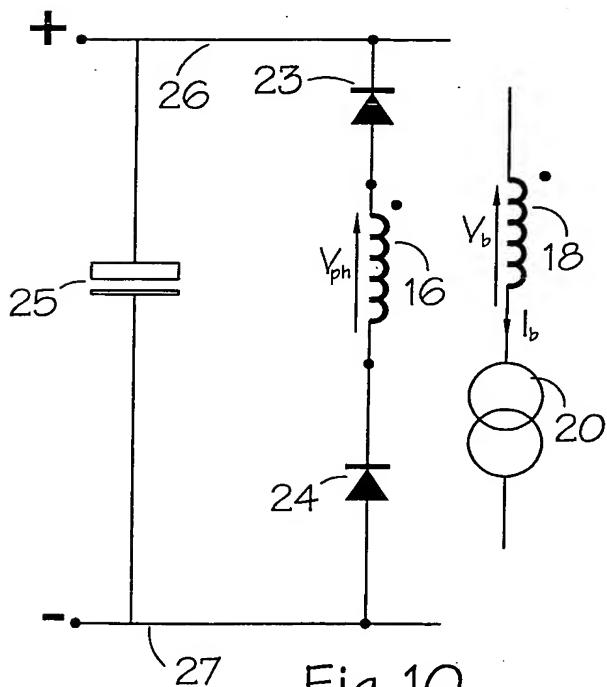


Fig 10

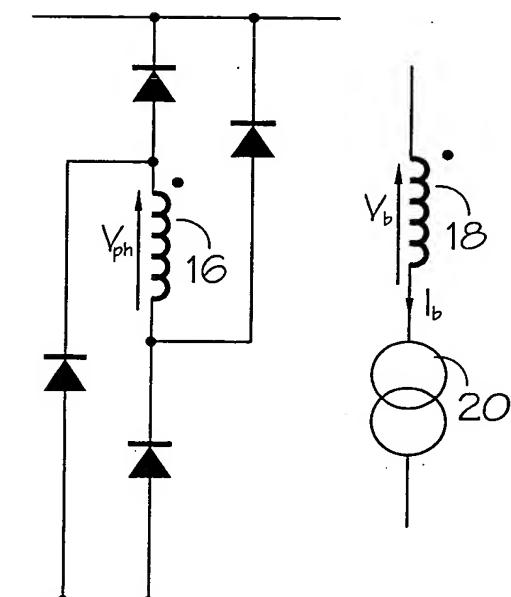
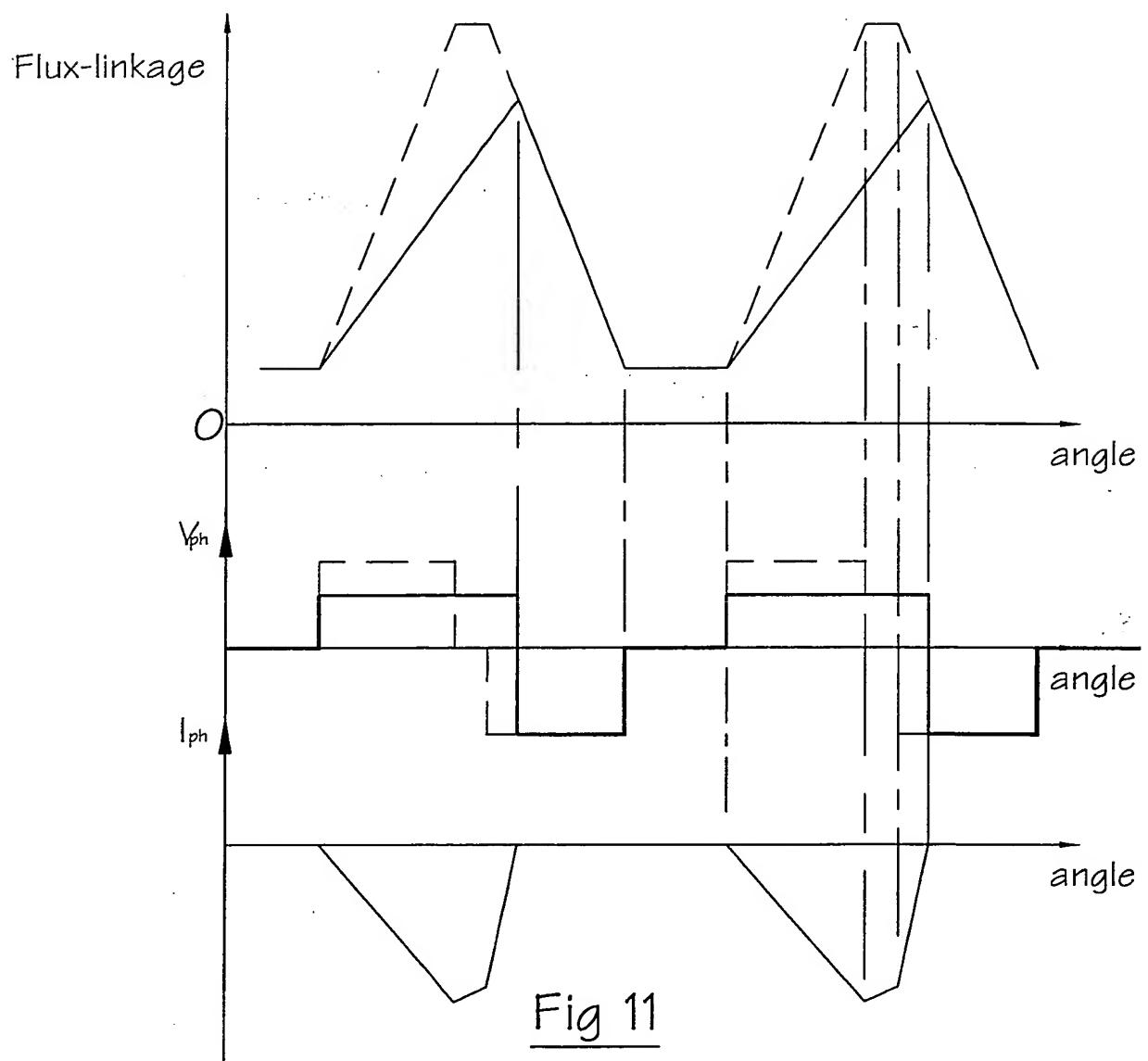


Fig 12





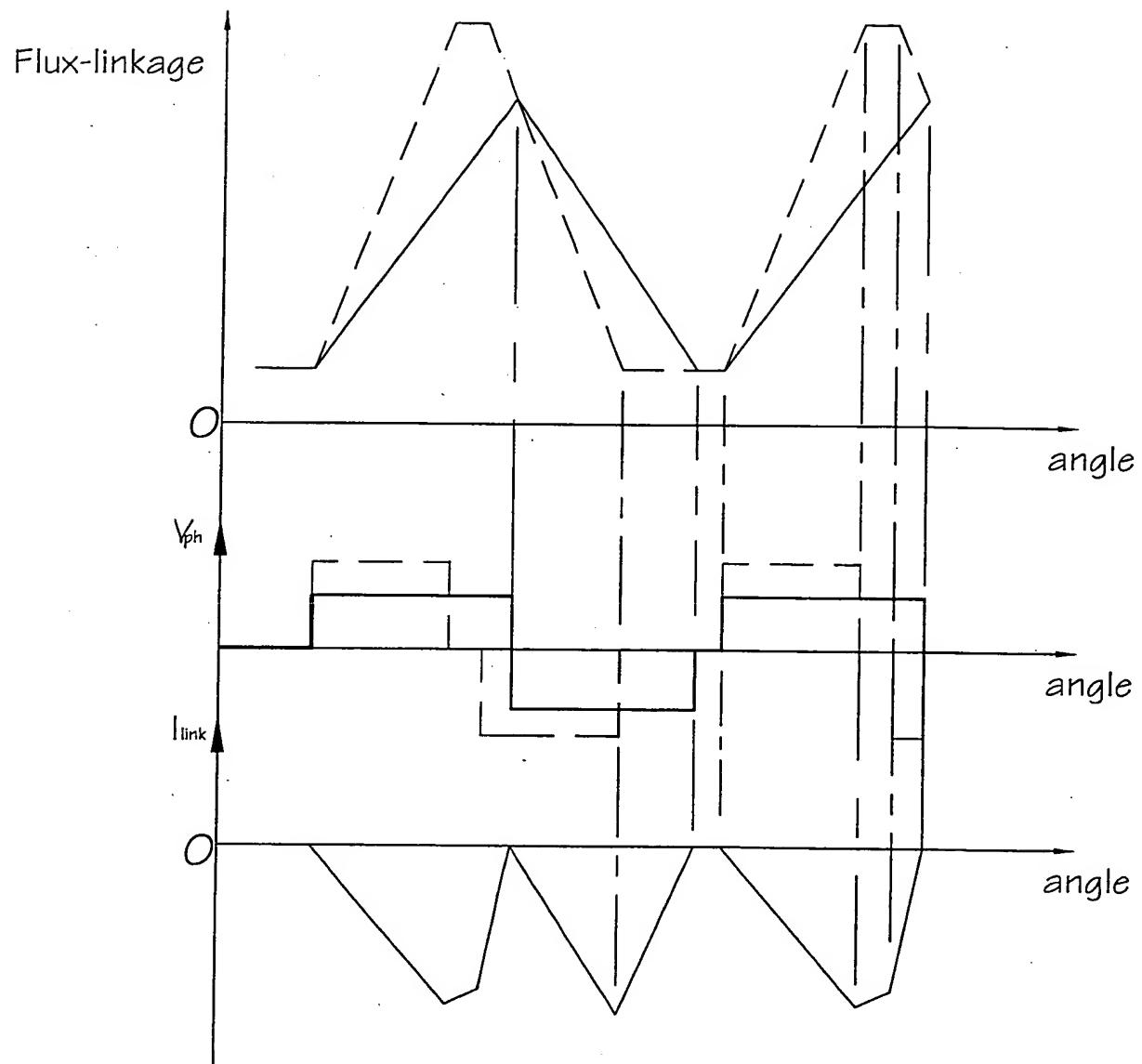


Fig 13



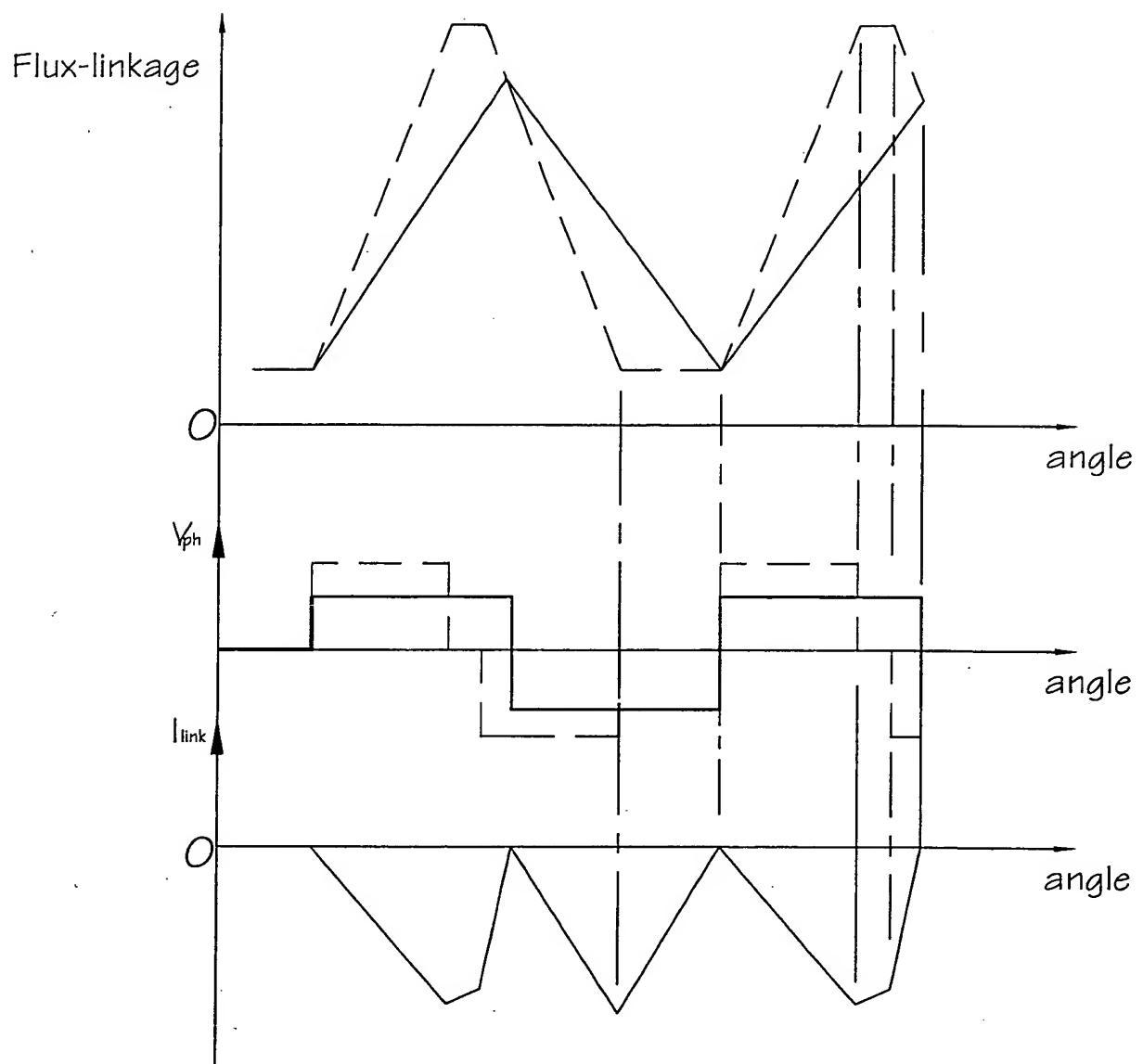


Fig 14



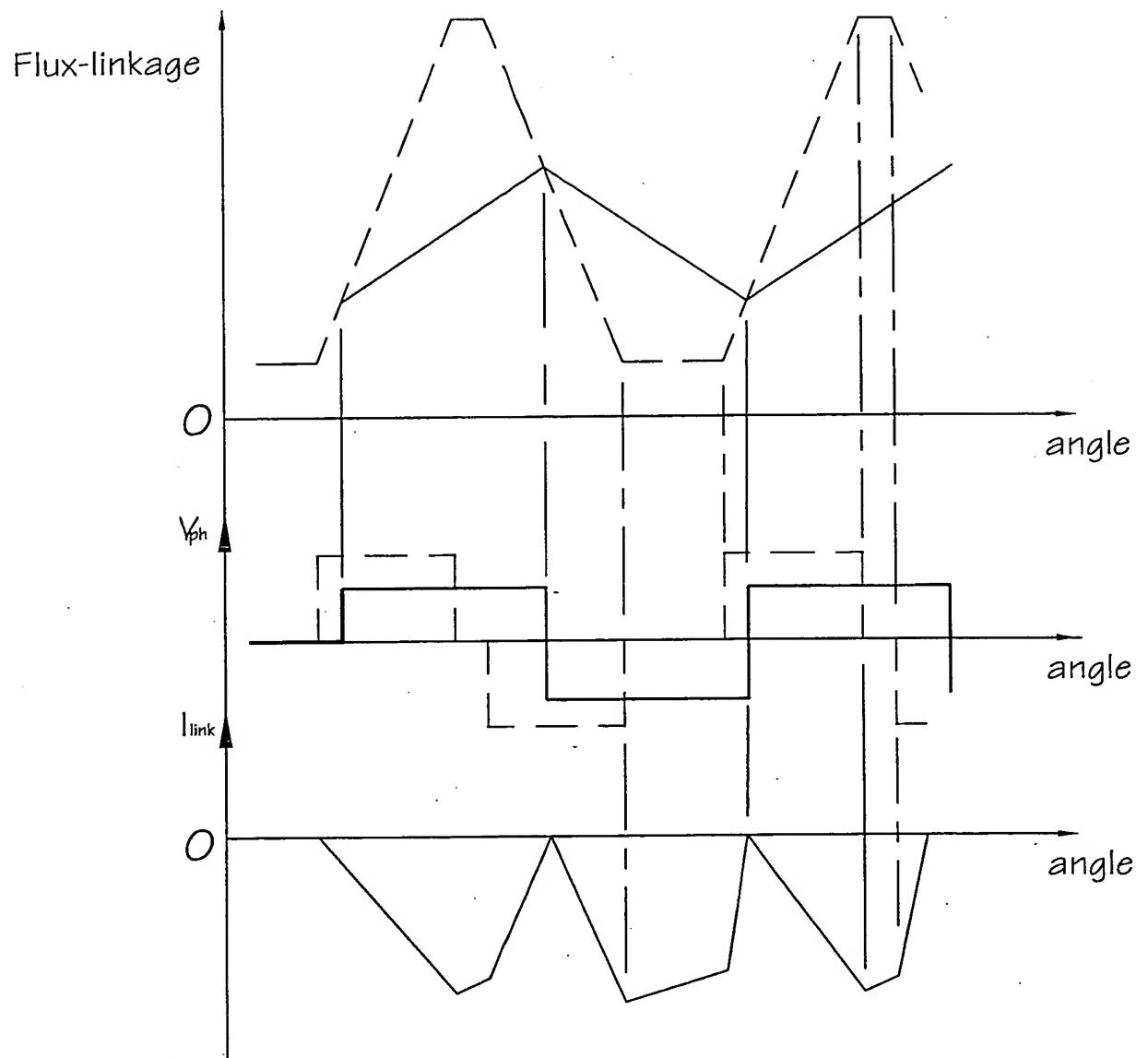
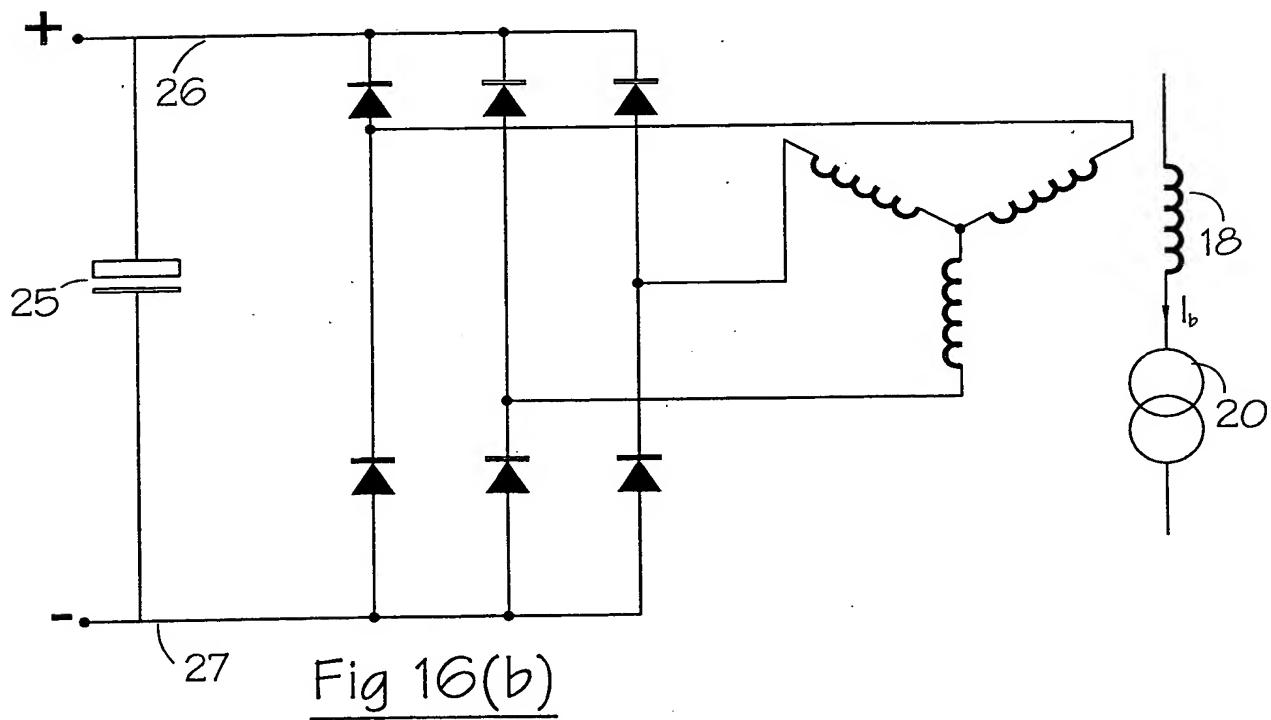
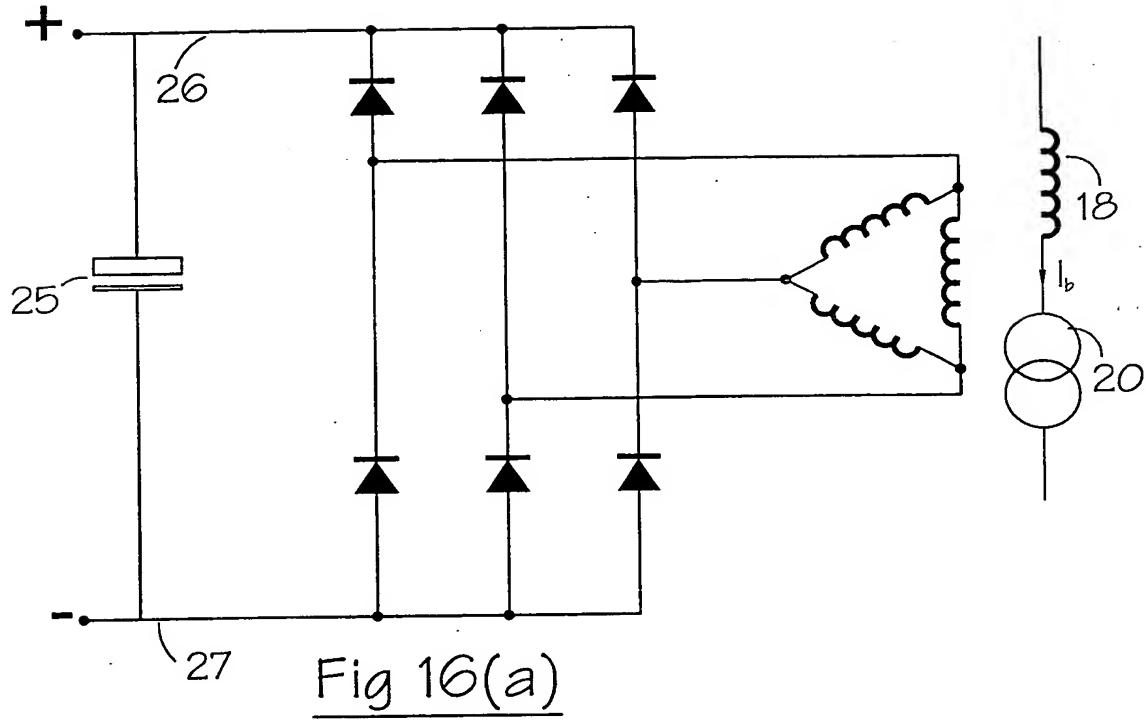


Fig 15





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